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An approach to computer-aided quality control based on 3D coordinate metrology

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Abstract

The quality of manufactured products usually needs to be verified. This paper presents an advanced CAQ approach to compare manufactured objects with reference data from underlying CAD models. First, an overview about the current state-of-the-art in optical 3D measurement techniques is given. After that the research method adopted in this paper is discussed. Furthermore, a software prototype of the presented approach in which a stripe projection system with combined gray-code and phase shifting is described. With this equipment, 3D shapes of objects or manufactured products can be measured. In order to compare the 3D data (represented in sensor coordinate system) a registration to the CAD coordinate system is needed. At first, the selection of a starting point for the orientation parameters is described. For the registration process different numerical algorithms are used to minimize a distance function. To achieve a better performance, an optimization process based on 3D voxel arrays is introduced. After the registration process, several parameters for the kind of geometric displacement can be calculated and visualized. For objects that cannot be measured from one direction, a pair-wise registration as well as a global registration have been developed. Furthermore, some rapid prototyping examples to which our CAQ approach has been applied are presented. Those examples show that our method works well in practice. Finally, some application fields for the CAQ approach presented here are outlined.

Keywords: Computer-aided quality control; Computer-aided manufacturing; Rapid prototyping; Coded light approach; 3D coordinate metrology

1. Introduction

In recent years the entire process from computer-aided product design to manufacture has reached an almost ultimate perfection. However, nominal/actual value comparisons show that there are always deviations between a manufactured product and its underlying CAD model. Reasons for that are, e.g. tool wear, thermal expansion, material defects, etc., things that are due to the nature of mechanical engineering, of course. In the range of computer-aided quality control the above-mentioned deviations have to be verified to detect part variations or to make tolerance conformance decisions. Today, there are powerful state-of-the-art coordinate measurement systems available that have provided industry with outstanding tools for expecting complex parts. Meanwhile, the majority of these systems is based on 3D metrology that has brought a significant change in modern coordinate measurement. The major difference to traditional measurement methods is that 3D metrology systems generate surface coordinates of a measured part instead of measuring its geometric dimensions. Having a collection of digitized surface points, details concerning part variation can be observed. Furthermore, various sections of different geometric features can be measured in a single process. Once a set of measurement data is collected, an independent numerical analysis must be performed to find a basis for a subsequent comparison between the measured feature and the corresponding reference data from its CAD models counterpart. This is the main goal of the approach presented in this paper. A more comprehensive introduction to 3D metrology as well as an overview about related work in this field can be found in [8].

This paper presents a non-contact metrology approach that can be used for various tasks in computer-aided quality control and rapid prototyping. It will be discussed throughout the whole paper and can be summarized as follows. Manufactured objects are measured by a stripe projector

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system based on a coded light approach combined with phase shifting. For image acquisition a standard video camera is employed. The sampled surface points measured in sensor coordinate system, typically 200.000–400.000 per image, are transferred into a CAD coordinate system. After selecting a rough orientation, either in an interactive manner or by a priori knowledge (automatic orientation without a priori knowledge can also be achieved by using fixed marks on the object's surface), a sophisticated numerical optimization process is started to determine the exact orientation that means to align the CAD model and the measured data set. A problem that occurs whenever objects cannot be captured from a single 3D sensor within one image has been solved by applying an additional orientation process. Measured data sets captured from different directions can either be orientated relatively to each other or transformed into a common coordinate system. For a nominal/actual value comparison, the distance from the data set to the underlying CAD model can be calculated point by point. The evaluated results can be visualized in many statistical ways, e.g. as difference per measured point, minimum, mean or maximum difference within a CAD element (e.g. an STL triangle).

The approach proposed in this paper has been successfully applied to several stereo-lithographic rapid prototyping objects and produced remarkable results. It supports quality control for all kinds of rapid prototyping and/or NC manufactured objects and is especially suited for an integration of CAQ into CAM processes. In that way two essential independently performed processes can be combined to make the overall process of product development more efficient.

2. Methods and principles

2.1. 3D coordinate measurement

Today, there are various measurement systems available which are based on very different approaches. These measurement techniques can be classified into active and passive methods. In general, passive approaches are used to calculate the shape of an object by interpreting rather special object characteristics. These methods usually depend on precise a priori knowledge of the related objects and therefore are not appropriate to meet general industrial requirements. Hence, they will not be discussed here in more detail.

Active measurement methods usually do not depend on special object characteristics and can be classified into contact and non-contact methods. An example of a contact system is the classical CMM (coordinate measuring machine) that samples discrete points of the related part using a mechanical sensor. To capture a complete shape, the sampling has to be performed in two directions. Although this method provides maximum accuracy, it is quite time consuming and cannot be used for soft materials that must not be touched. Therefore, it does not always meet contemporary industrial requirements. More relevant to industrial needs are non-contact systems. They will be considered further on in this paper, the focus being on optical non-contact methods. Beyond those, there are further methods that might be applicable as well, e.g. microwave-based radar or ultrasonic-based measurement, but they are not relevant for the research method adopted in this paper.

The majority of employed systems is based on the following principles: spot triangulation, stripe sectioning, coded light approach, and interferrometrical methods. Since the last three methods are restricted to reflective materials, they are not well suited for general purposes. Hence, they will not be specified here, in contrast to the triangulation methods that will be considered in more detail.

Within the triangulation principle a point on an object surface can be determined by the trigonometric relations between a camera, a projector and the object itself (cf. Fig. 1). Suppose that all geometric parameters are known, the distance from the baseline to the object can be calculated according to Eq. (1):

$$d = b\frac{\sin\alpha\sin\beta}{\sin(\alpha+\beta)} \tag{1}$$

For a complete object digitization the projected spot has to be moved in two directions to sample the object in lines, point by point. This kind of sampling can be realized, e.g. by employing two sweeping mirrors. Obviously, the measurement accuracy is highly influenced by the angular precision of the spot movement mechanism. According to this, the error propagation of the depth measurement error Δd can be calculated according to (Eq. (2)):

$$\Delta d = b\frac{\sin^2\beta\,\Delta\alpha + \sin^2\alpha\,\Delta\beta}{\sin^2(\alpha+\beta)} \tag{2}$$

Since the spot direction α is fixed, only the parameter β needs to be determined. For spot triangulation, usually 1D sampling devices (sensors), such as line cameras or PSDs are employed. A comprehensive discussion of the mathematical background can be found in [4].

To overcome the limitation of single point scanning, the so-called stripe-shaped illumination method can be employed. Hereby a plane of light intersects an object and the corresponding image is a profile. A standard camera can be used to inspect the line shifting caused by the object's

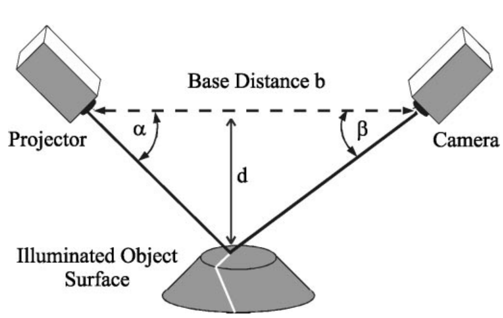

Fig. 1. Triangulation principle.

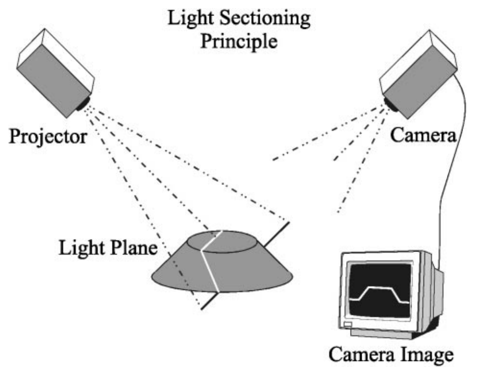

Fig. 2. Light sectioning principle.

height. The mathematical calculations in general remain the same as for spot triangulation, but for each image it is now possible to measure a whole line or profile, respectively (cf. Fig. 2). In contrast to spot triangulation, the projected light plane has to be moved only along one axis to sample the whole object.

To decrease the sampling time again, a more sophisticated approach — the so-called coded light approach (cf. Fig. 3) — can be employed. This is the method used in the software prototype of the metrology system presented in this paper. Hereby a sequence of line patterns is projected onto the object of the surface. For this purpose, usually an ordinary LCD is used. To cope with larger objects, new projector technologies such as micro-mirror technology DLP (digital light processing by Texas Instruments [5]) or light valves D-ILA (direct drive image light amplifier by JVC [6]) might also be used. The basic idea behind the coded light approach is to encode the particular lines of the used projector into subsequent patterns by using a simple gray-code. As shown in [4], the encoding of N lines requires a minimum of $\log_2 N$ bits. The subsequent bits of each single line are sequentially projected and for each camera pixel it has to be checked whether the corresponding projector line is light or dark. Based upon these checks, the so-called bitplane stack can be built-up [4]. When the coding process is finished, each camera pixel bears the information of its corresponding projector line. Assuming that we have a correct sensor calibration, the projection angle α can be derived directly from the projector line number. Since the camera device can be calibrated before starting the measuring process, the angle β is fixed for each individual camera pixel and the relating triangulation can be calculated. Obviously, the calibration needs to determine the functional dependencies between the line number (projection line) and the projection angle α as well as between the angle β and each camera pixel. Since the line number is an integer, the angular precision for a projector with 640 lines is only $\frac{1}{640}$ of an image under scope. Since the precision of the depth measurement depends on the angles α and β (cf. Eq. (2)), it is desirable to improve the resolution mentioned above. A sophisticated method to achieve this is to combine the binary gray-code with the so-called phase shifting procedure [4]. The idea behind this process is to use a lateral line modulation in terms of a harmonic function (sinusoidal). The resulting pattern can laterally be shifted by a constant angle so that general phase shifting algorithms can be used to determine positions in a split line. For a line projector with 640 lines, a minimum of only 10 images has to be taken for the whole encoding. In order to make the evaluation process more robust and accurate, some additional patterns can be used (e.g. to determine the object texture). Our current implementation uses 14–18 images (phase shifting included). In comparison to light sectioning where 640 images would have to be taken, the coded light approach increases the processing speed by a factor greater than 30. Furthermore, it is possible to run the projector in the so-called video real-time mode that means with a maximum capturing speed of 25 images per second. For real-time applications, the combination package of video camera and frame-grabber must be capable to get those 25 frames per second completely. Suitable for such requirements is a full frame integration or the so-called progressive scan camera. With such a setup, a whole sequence can be captured in less than 1 s.

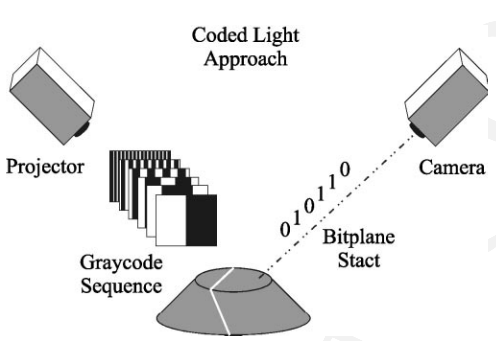

Fig. 3. Coded light approach.

In our prototype implementation, a line projector LCD-640 from ABW GmbH was used for image acquisition combined with the software package ABW-VIS [7] and two standard video cameras having a resolution of 768×576 pixel (cf. Fig. 4). The ABW-VIS software package allows to control the entire measurement process, that means projector programming, image grabbing with a frame-grabber as well as the whole measurement and calibration process. The transformation calculations for the sampled points can be performed using standard hardware (Intel Pentium II processor, 300 MHz) within about 5 s. As a result of each measurement, we get images in which each pixel has corresponding $x/y/z$ coordinates, a gray value and a masking bit that states whether the related pixel was measurable or not. These images form the basis for any further signal processing. At this point it has to be stressed that all signal processing procedures have to cope with missing pixels caused by shadows or surface textures.

Fig. 5 shows an example of a visualized measured data set. The z-coordinate of each measured pixel is gray-level coded. An additional profile shows the z-coordinate (profile)

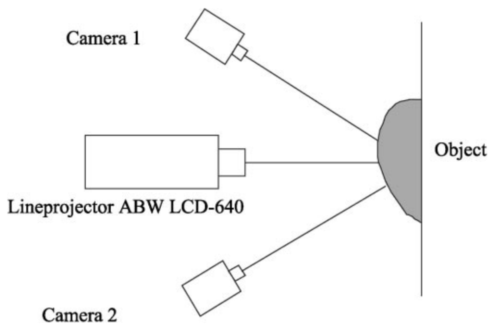

Fig. 4. Principal measurement setup with one projector and two cameras (top view).

along a horizontal and a vertical line. Analogously, for each pixel the corresponding x and y values might be presented in this way, too. The not measured and therefore masked pixels (shadows, textures) are drawn white in this picture.

2.2. CAD model reference data

In order to compare manufactured objects with their underlying CAD models, a universal and standardized data exchange format is required. Since most of the sample parts presented in this paper are rapid prototyping objects manufactured with a stereo-lithographic device, the STL (standard triangulation language) format has been chosen to describe the related objects. STL is widely used for manufacturing of rapid prototyping objects and almost every professional CAD package is able to export STL files. In the following sections, only triangular patches are used for object approximation tasks. All algorithms used in the prototype implementation can be adapted to other geometric forms, such as cylinders, cones or more complicated surface patches, e.g. 3D Beziér patches or NURBS.

2.3. Coordinate transformation

In general, it is not possible to locate a manufactured object within a measurement set-up in exactly the same coordinate system that originally has been used to design the object in a CAD environment. In order to compare the measured data set with reference data from the underlying CAD model it is necessary to transform the sampled data into the coordinate system of the corresponding CAD model. In literature, this process is usually called registration.To

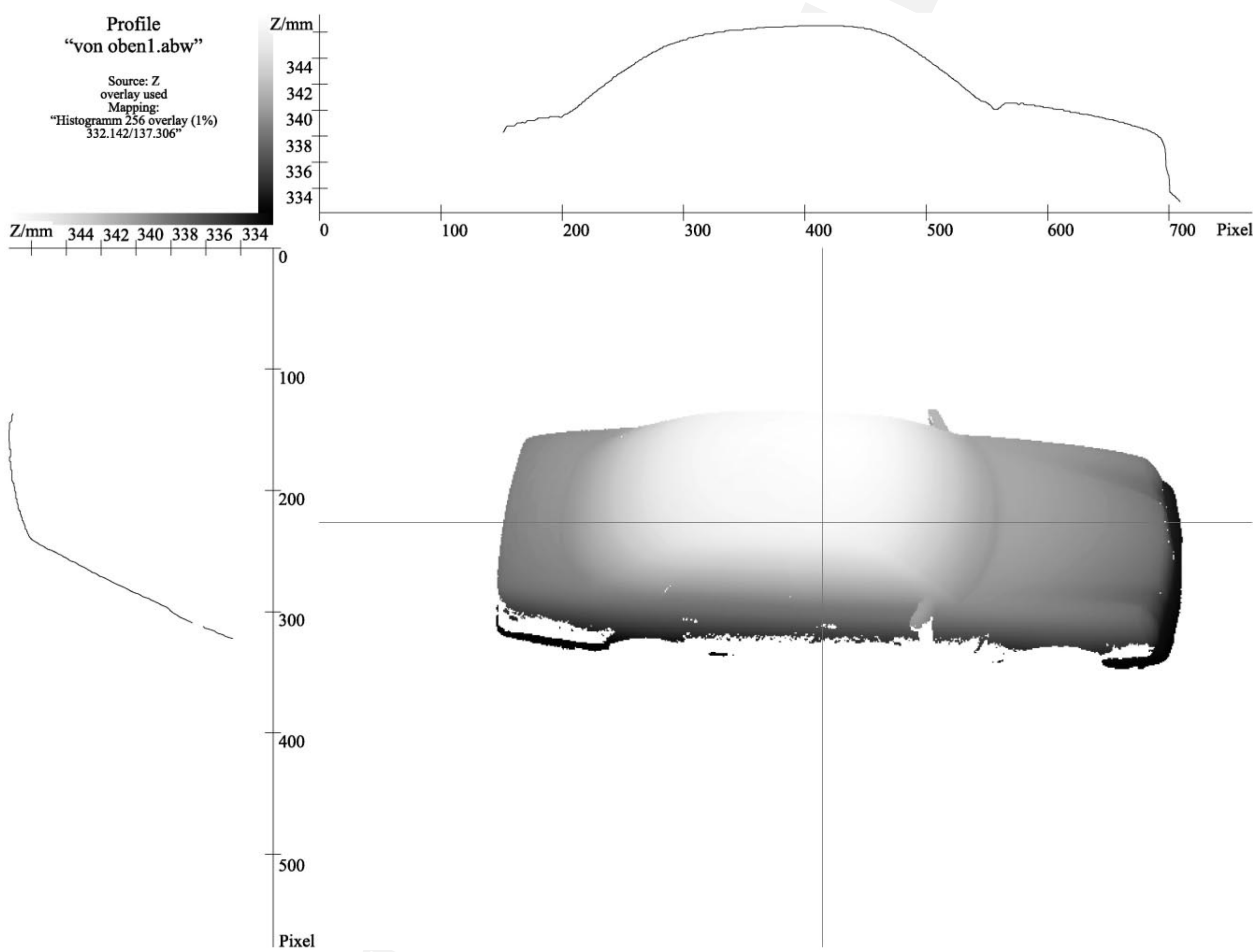

Fig. 5. Example of a visualized data set showing a z-coordinate based depth image and a corresponding profile along a horizontal and vertical line.

determine the correct transformation parameters the correlation between the measured data set and the CAD model has to be expressed in terms of a mathematical function. We will denote this functional dependence between the relative orientation parameters to be found, the correlation between the measured data set (in transformed sensor coordinate system) and the reference data (in CAD coordinate system) as distance function f_{dist}. The definition of this function is very important in order to find the desired orientation parameters. In this paper, we approach this problem by using a special kind of least-squares fit as follows. For any measured point find the nearest CAD triangle and sum up the square of all nearest distances as stated in Eq. (3). In order to optimize this searching procedure we define an upper bound $d_{\max}$. In this way, the calculated distance can be limited to a constant maximum in case of sporadic outliers or measurement errors. With d_{ij}, we denote the perpendicular distance between a point i and a triangle j, and N denotes the number of measured points.

$$f_{\mathrm{dist}} = \frac{1}{N}\sum_{i=1}^{N} \mathrm{Min}(d_{\max}, \underset{j}{\mathrm{Min}}(d_{i,j}))^2 \qquad (3)$$

If no distance limitation ($d_{\max}$) would be used, sporadic outliers with large distances would be weighted with the square of their distance and might cause significant errors. It might also be possible to omit all points that exceed the distance of $d_{\max}$ at all.

For calculating the perpendicular distances between points and triangles, we consider only those points for which the corresponding orthogonal projection hits the related triangle. In concave part regions a point always has a perpendicular distance to at least one triangle (cf. Fig. 6 with point p and three triangles t_{1-3}). However, for convex regions this statement no longer holds true. There may be points (cf. p_2 in Fig. 7) for which the corresponding orthogonal projections are not inside a triangle. In such cases, the maximum distance $d_{\max}$ will be assigned as mentioned earlier. In Fig. 15, this effect can be observed. Particular pixels which have been assigned the distance $d_{\max}$ are displayed white and appear along the edges of the CAD elements. Although this situation is not desirable, the overall results are not affected. The points for which the calculated distance is greater than $d_{\max}$ might also be omitted altogether. A literature review on extreme fit problems and least-squares approaches can be found in [9].

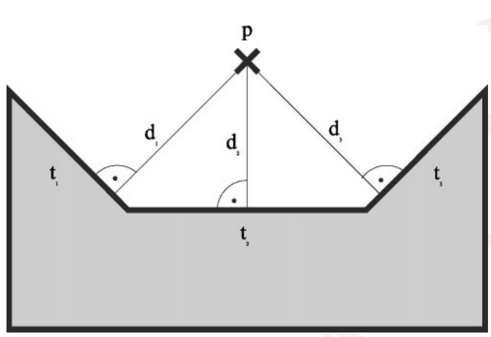

Fig. 6. Concave part of object surface.

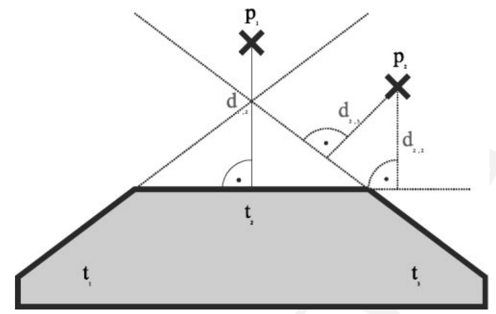

Fig. 7. Convex part of object surface.

2.4. Voxel arrays for process optimization

According to Eq. (3) one can imagine that the evaluation process for f_{dist} is very time consuming. The outer iteration loop runs over all measured points, usually about 200.000–400.000 per camera. The inner iteration loop has to pass all CAD elements of the exported STL file. To optimize the above-stated evaluation process, it is possible to restrict the search area by using rather special 3D arrays, the so-called voxel arrays. The idea behind this is to sort the triangles within 3D space in a way that the inner loop of Eq. (3) will not have to run over all triangles. To achieve this, all the triangles are sorted into the voxel array. After that each voxel element bears the information of all its intersecting triangles. Then the search procedure only needs to consider the triangles in and around the actual voxel. As shown in Fig. 8, the size of each voxel is set to $d_{\max}$. In this way, it can be guaranteed that for any given point all other points within a distance of $d_{\max}$ can be found in the adjacent voxels (p_j' is the closest point found on triangle j). In a 3D array, $3^3 = 27$ voxels have to be considered. All the others can be skipped and the evaluation time for Eq. (3) can be reduced enormously.

2.5. Starting values for the alignment process

In practice, it is usually not possible to have an automatism that can handle the orientation process for any given object [2]. For this reason, appropriate initial values for the six degrees of freedom (three rotation parameters and three translation parameters) have to be found before the optimization process for the alignment of the captured data set and the reference data from the CAD model can be started. There are several possibilities to determine such starting values. For interactive processing of different objects the simplest way is to define starting values in a manual manner. In our prototype this can be done by digitizing points on both the image of the CAD model and the depth image of the measured point set by simply clicking a mouse button. To define a relative orientation at least three corresponding points have to be picked. However, the more points are

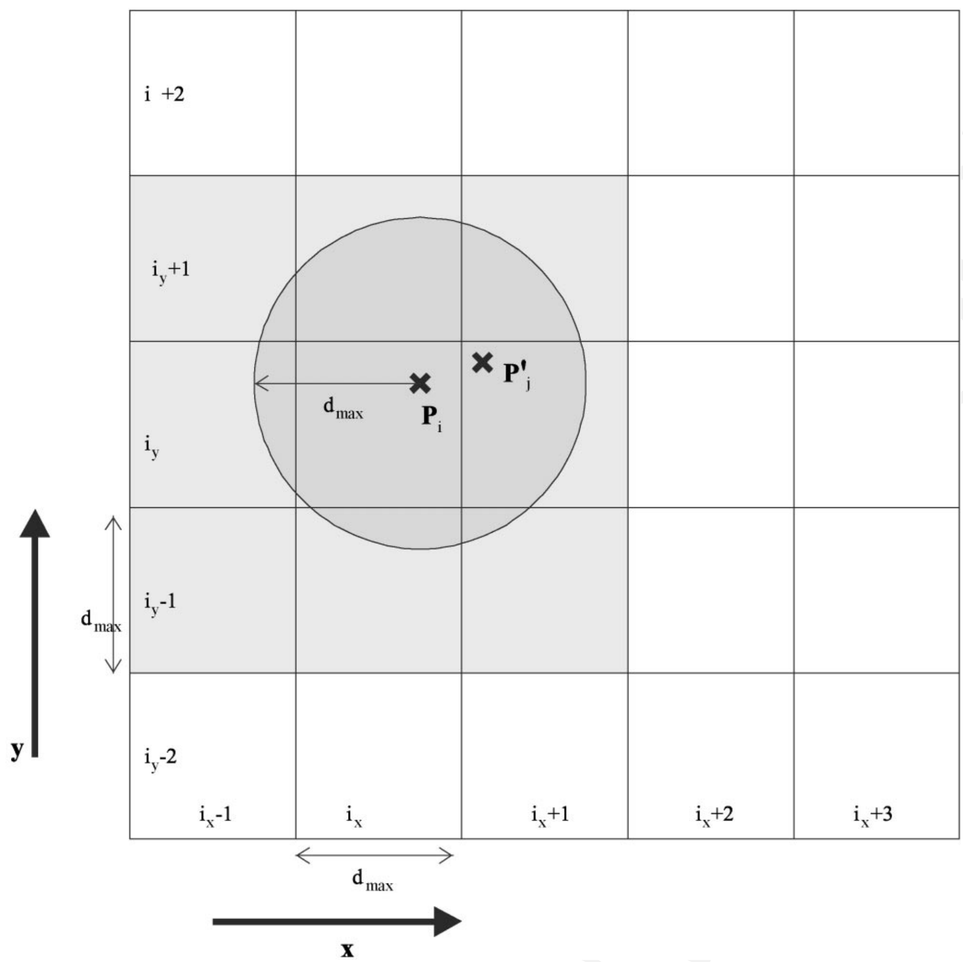

Fig. 8. 2D projection of the voxel array with searching radius d_{max}.

selected, the better the relative orientation will be. In applications where the objects to be measured are always identically positioned, e.g. on assembly lines, starting values have to be set up only once. Whenever such an exact object and device positioning cannot be assured, there should be at least three prominent points on the related object that can be detected automatically. Such pre-processing operations are very object-specific and have not been analyzed in detail within this project. Detailed discussions on sampling uncertainty in 3D measurement analysis and uncertainty of extreme fit evaluation can be found in [8,9]. In the examples shown below, the orientation process has always been performed in a manual manner as stated before. Fig. 9 shows the CAD model of a rapid-prototyping object (turbine). The corresponding measured rapid prototyping object is shown in Fig. 10. It has been manufactured using laser sinter technology and has a diameter of approximately 53 mm and a height of approximately 10 mm.

2.6. The registration process

After a rough initialization for the alignment has been arranged an iterative numerical optimization procedure for the orientation parameters is required. Hereby, the parameter values for the six degrees of freedom are modified in order to minimize the distance function (Eq. (2)). Several numerical algorithms have been tested for this task, e.g. the downhill simplex algorithm and some kinds of simulated annealing [1]. Furthermore, a modified ICP (iterative closest point) algorithm taken from [2] is currently being tested in our implementation. The basic idea behind that algorithm is to use a closed form solution for the registration of corresponding points that has been described in literature first by Horn [3]. This algorithm calculates the rotation parameters by evaluating the eigenvalues of a rather complicated 4×4 matrix that can be derived from the sum of all cross-covariance matrices. More detailed information on this, the interested reader can find in [2].

The downhill simplex algorithm mentioned above just crawls downhill by testing some parameter variations. Only straightforward steps that lower the optimization function will be performed. The advantage of this general approach is that the algorithm makes almost no special assumption about the optimization function. The calculation time for the example shown in Fig. 7 with downhill simplex took 8 min 44 s, the convergence is shown in Fig. 11.

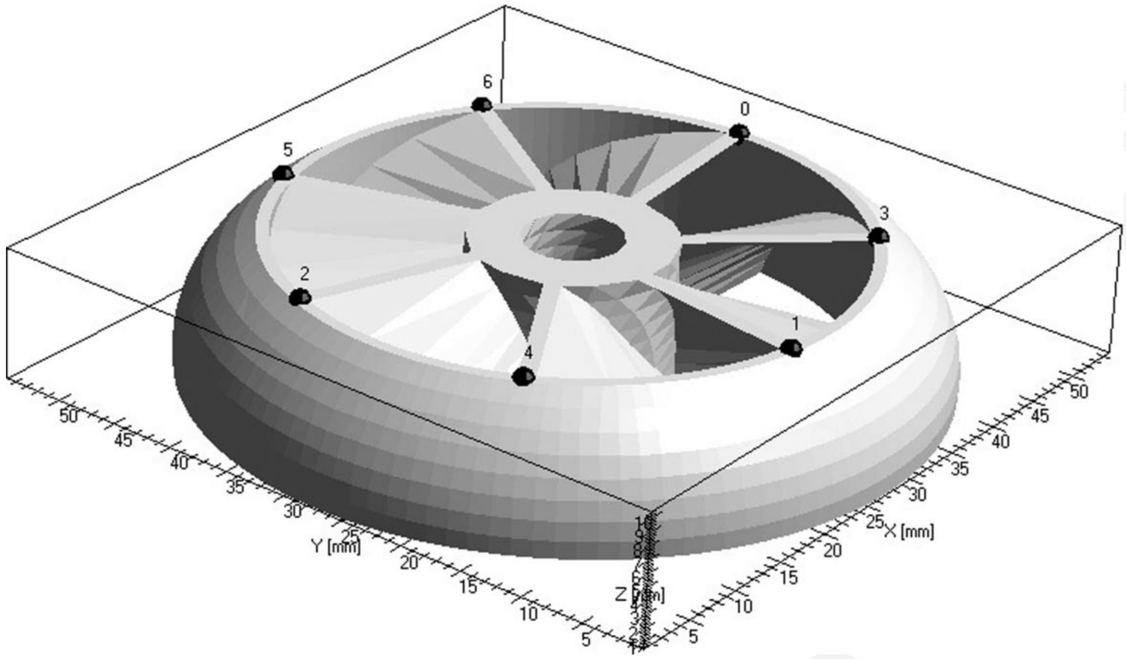

Fig. 9. Selected points in CAD data set (6618 triangles).

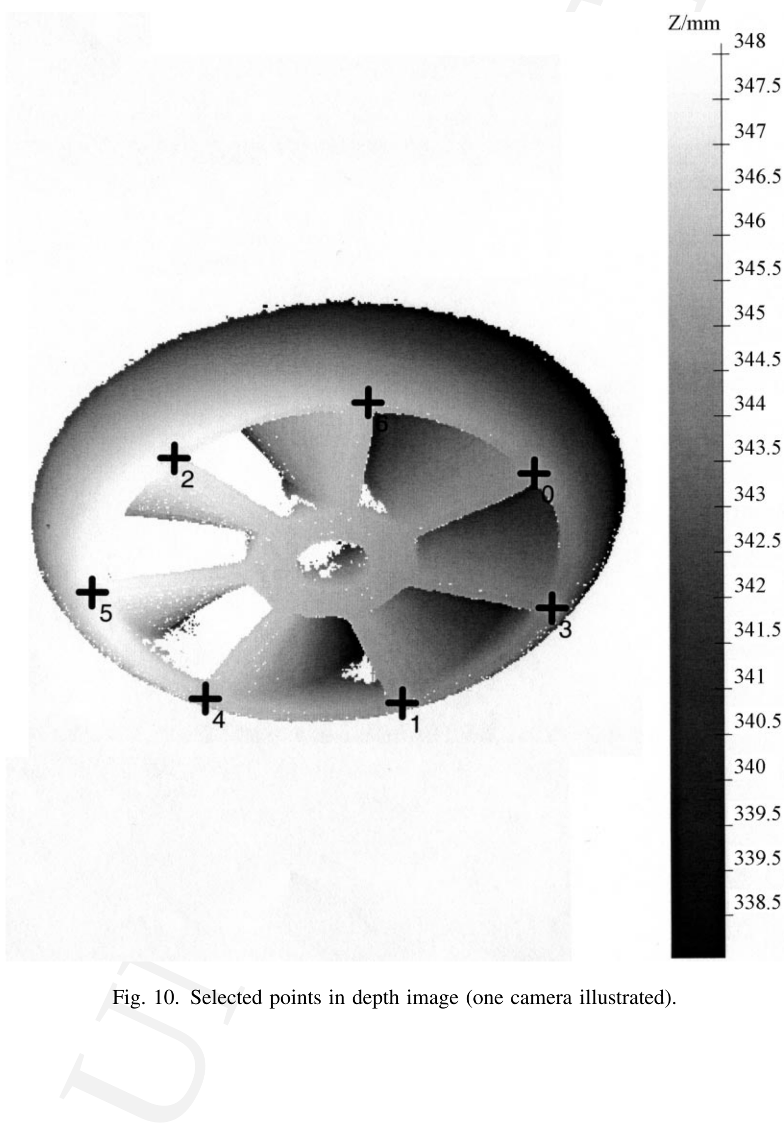

Fig. 10. Selected points in depth image (one camera illustrated).

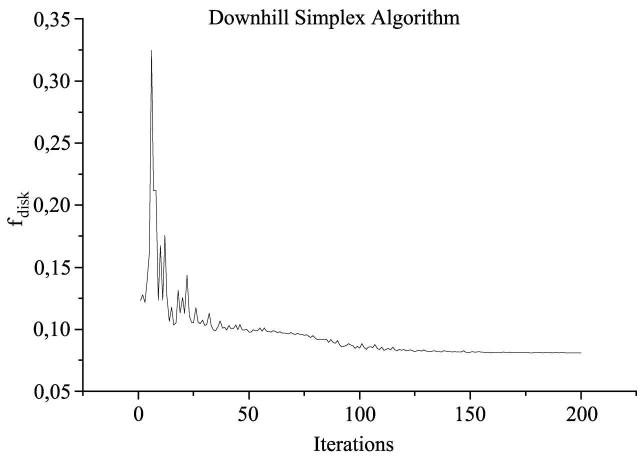

Fig. 11. Numerical optimization procedure based on downhill simplex algorithm.

The ICP algorithm taken from [2] is said to achieve a much faster convergence (more than factor 100). We are currently testing this algorithm and for the time being in our implementation we have observed an increased performance of about factor 10. The implementation of this algorithm into a system running on the most powerful hardware available today, should allow to employ our advanced CAQ approach in line production environments. If the object orientation in line production is known to be reproducible with measurement precision, the starting value definition and the registration process have to be carried out only once.

3. Results

A comparison between the measured data and the corresponding CAD model can be realized in various ways. It is possible, e.g. to map the deviations into the CAD element (STL triangle) or to visualize the difference of each measured point. On the CAD element, statistical values have to be used, because a CAD element usually corresponds to many points. Available statistical features are minimum, mean or maximum distance as well as the standard deviation and the number of corresponding points. Since the distance between a point and an oriented triangle can be positive or negative, the mean distance should be used with care. In general, it will be better to have a look at the standard deviation. For large elements it may be more useful to calculate a histogram of all assigned point distances.

Fig. 12 shows the deviation between the CAD model and the measured data for the turbine example already presented above. It is interesting in the context of this object that a formerly unknown error in one axis (in the illustration, orientation nearly vertical) could be detected. Obviously, the rapid prototyping device performed an undesired scaling in this axis, so that the manufactured object appears to be a little bit squeezed.

Another demonstration object is presented in Fig. 13. It shows the CAD data set of a car. The corresponding rapid prototyping object shown in Fig. 14 has been manufactured with stereo-lithographic technology. The object size is approximately 80 mm × 33 mm × 24 mm. To get a starting point the orientation was manually defined by corresponding points (cf. Figs. 13 and 14).

The remaining differences between both data sets after the optimization process are mapped into the measured data set (cf. Fig. 15). An overview of the differences can be visualized as a histogram (cf. Fig. 16). As mentioned earlier, the differences can also be visualized in the CAD data. Figs. 17–19 show some possible results.

3.1. Multiple measurement registration

The problem that arises for objects that cannot be measured from the 3D sensor device within one image has been solved by an additional orientation process. Measured data sets captured from different directions can be oriented relatively to each other or may be transformed into a common coordinate system. The registration procedure is generally the same as for CAD data registration considered before. Only the distance function needs to be exchanged. With R as rotation matrix, t as translation vector, p and p' the points of the two measured data sets, we define

$$f_{\mathrm{dist}} = \frac{1}{N}\sum_{i=1}^{N}\mathrm{Min}\left(d_{\max}, \underset{j}{\mathrm{Min}}\left(|p_i - (Rp'_j + t)|\right)\right)^2 \qquad (4)$$

As described above, pixels with a distance greater than $d_{\max}$ can be omitted. Various tests have shown that the strategy of omitting these points provides the best results. From now on these pixels are always skipped and the total number of pixels N is adjusted accordingly. That means, N is the number of actually used pixels. In this way also the voxel array optimization becomes to some extent more effective because the two nested iteration loops run over a reduced set of measured points.

In Figs. 20 and 21, a comparison between the downhill simplex algorithm and the ICP algorithm for optimization is shown for both good and bad starting values. Both figures show the number of used pixels and the trend of the optimization function f_{opt}. In the example shown in Fig. 20, the manual pre-orientation has been chosen very carefully. This means that the starting values for the optimization process are good. Taking a look at this figure, it can be seen that the number of used pixels (remember that all these pixels have a corresponding counterpart in the other data set within $d_{\max}$) at the beginning of the procedure is almost as high as at the end of the procedure. Hence, the pre-orientation must have been almost as good as $d_{\max}$.

Obviously, the ICP algorithm works much faster and better than the downhill simplex algorithm. In the example shown in Fig. 21, the manually selected starting values have

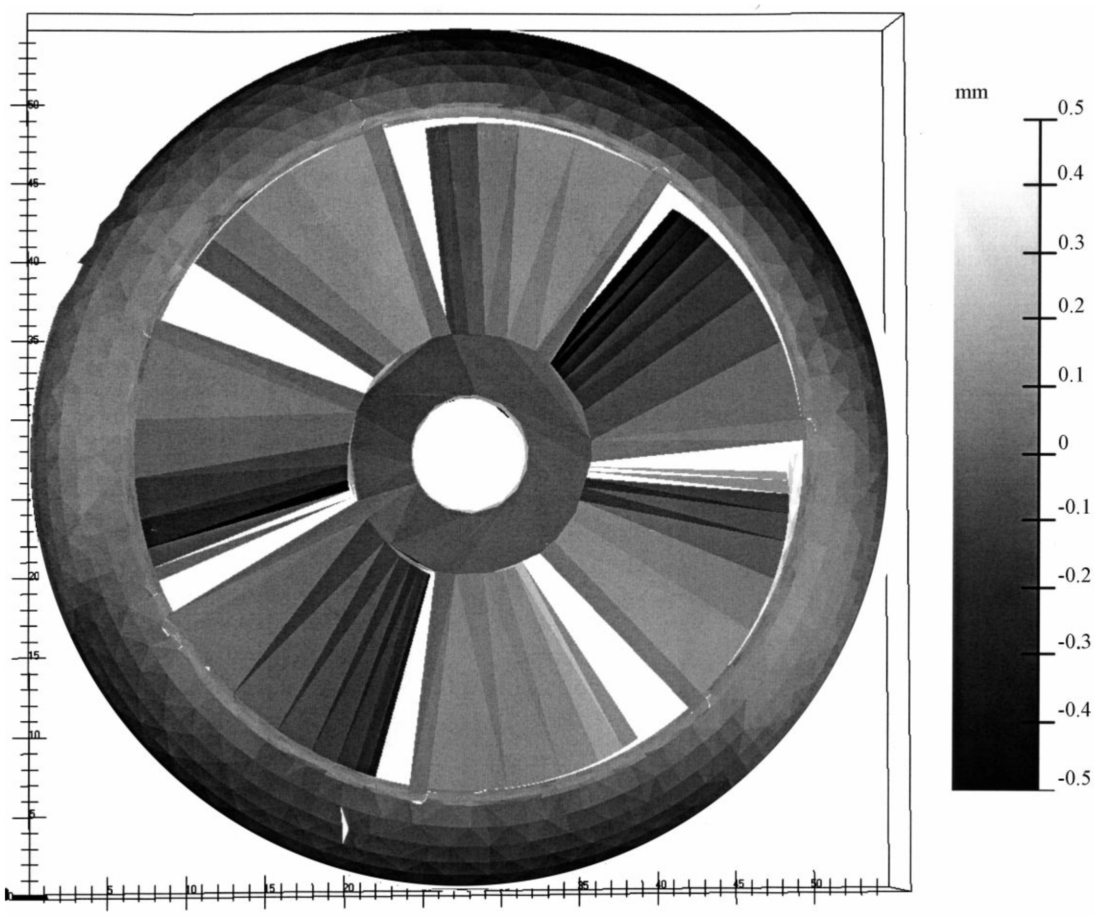

Fig. 12. Deviation of each CAD triangle to the measured object.

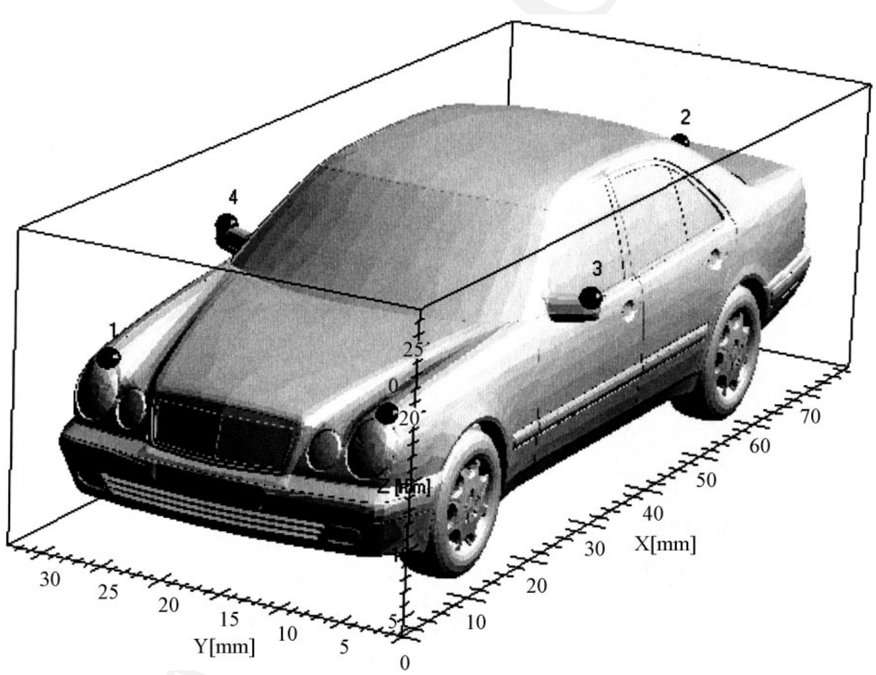

Fig. 13. Points selected in CAD data set (24 314 triangles).

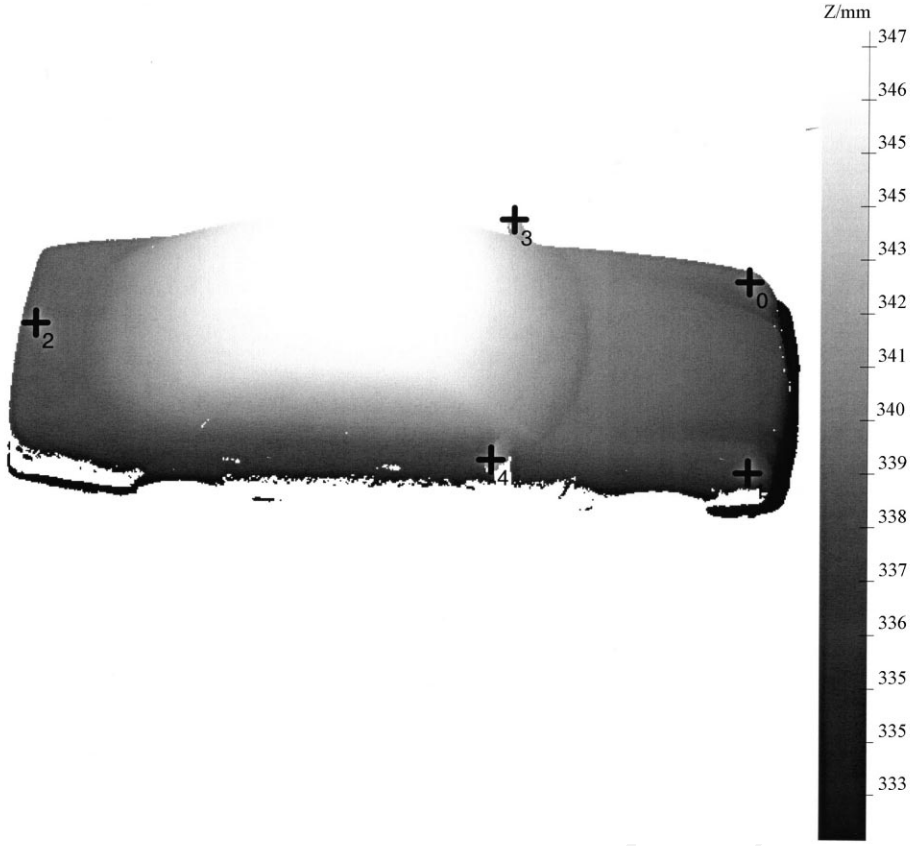

Fig. 14. Points selected from measured depth image.

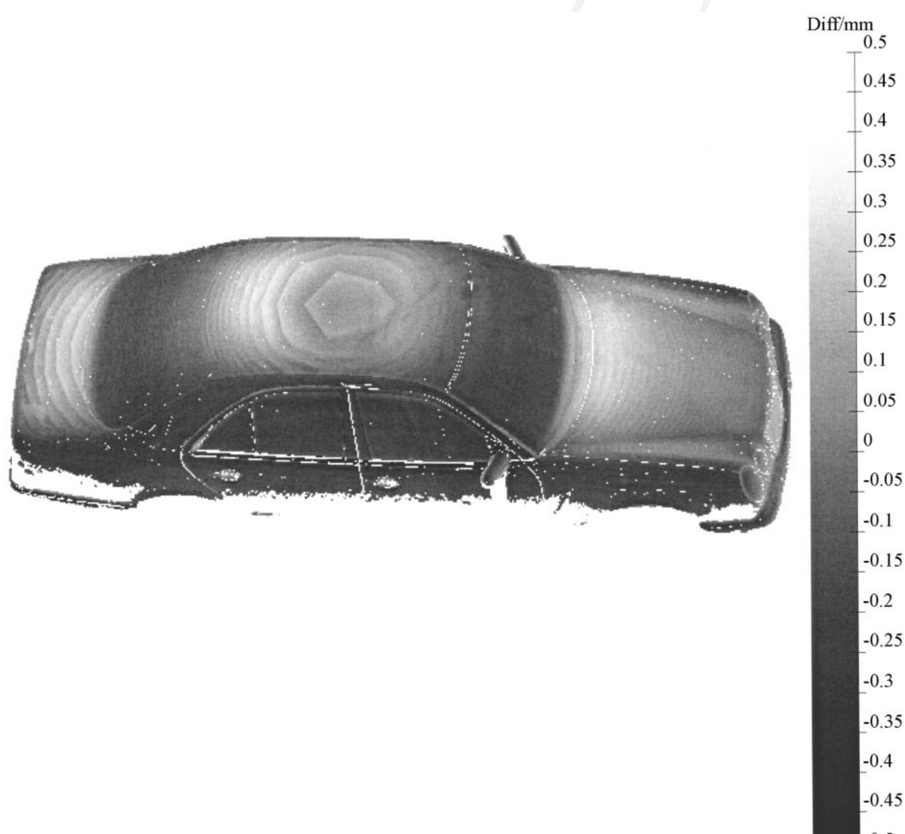

Fig. 15. Remaining differences after registration, the layers of the stereo-lithographic production (0.1 mm) are clearly visible.

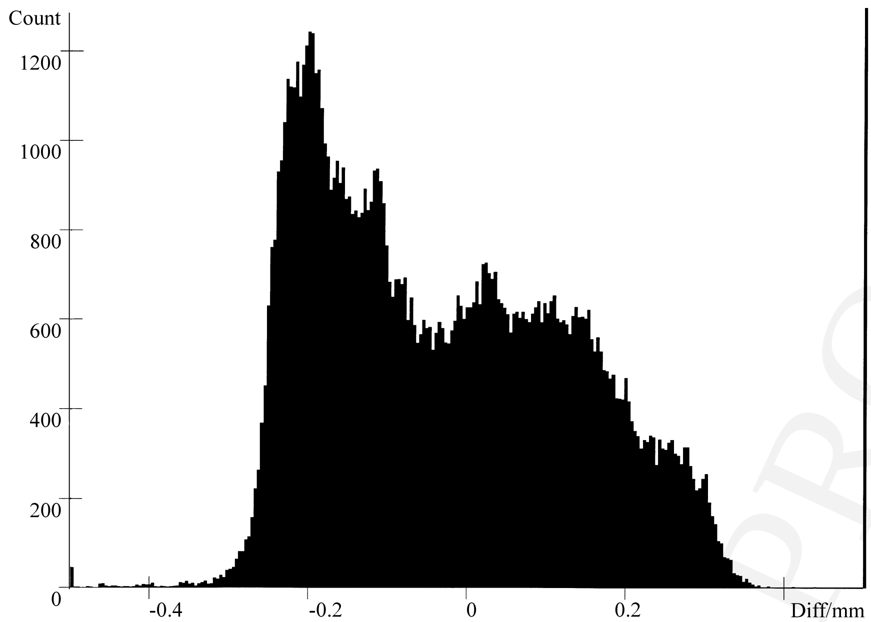

Fig. 16. Histogram of differences after registration.

been chosen much worse. Here, the advantage of the ICP algorithm is amazing. The competing downhill simplex algorithm cannot temporarily worsen the optimization function to get more pixels in a distance less then d_{max}. The ICP algorithm has no problem to find an orientation for which much more pixels have a better average distance.

Figs. 22 and 23 show measured data sets of another rapid prototyping object from different directions (the object has

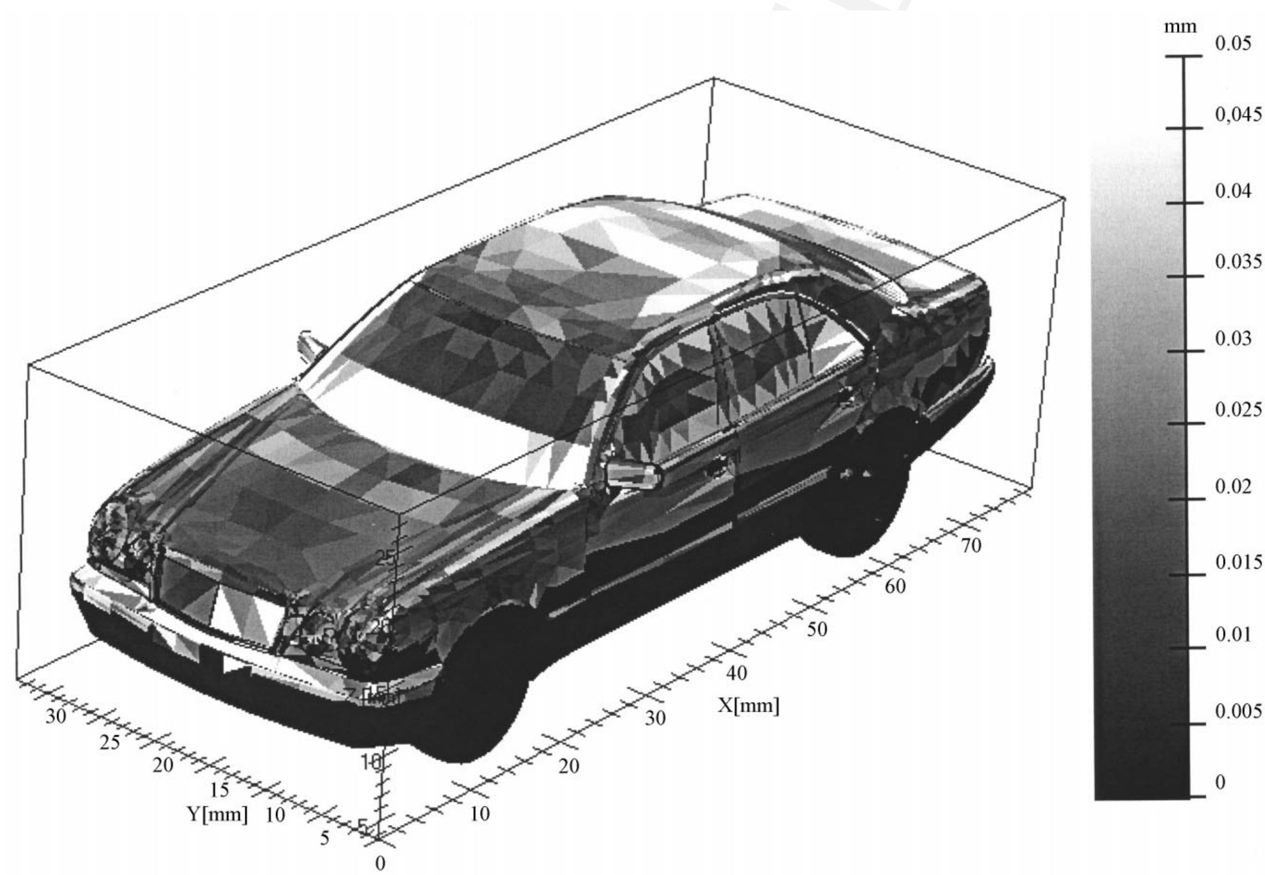

Fig. 17. Standard deviation of the CAD elements after registration.

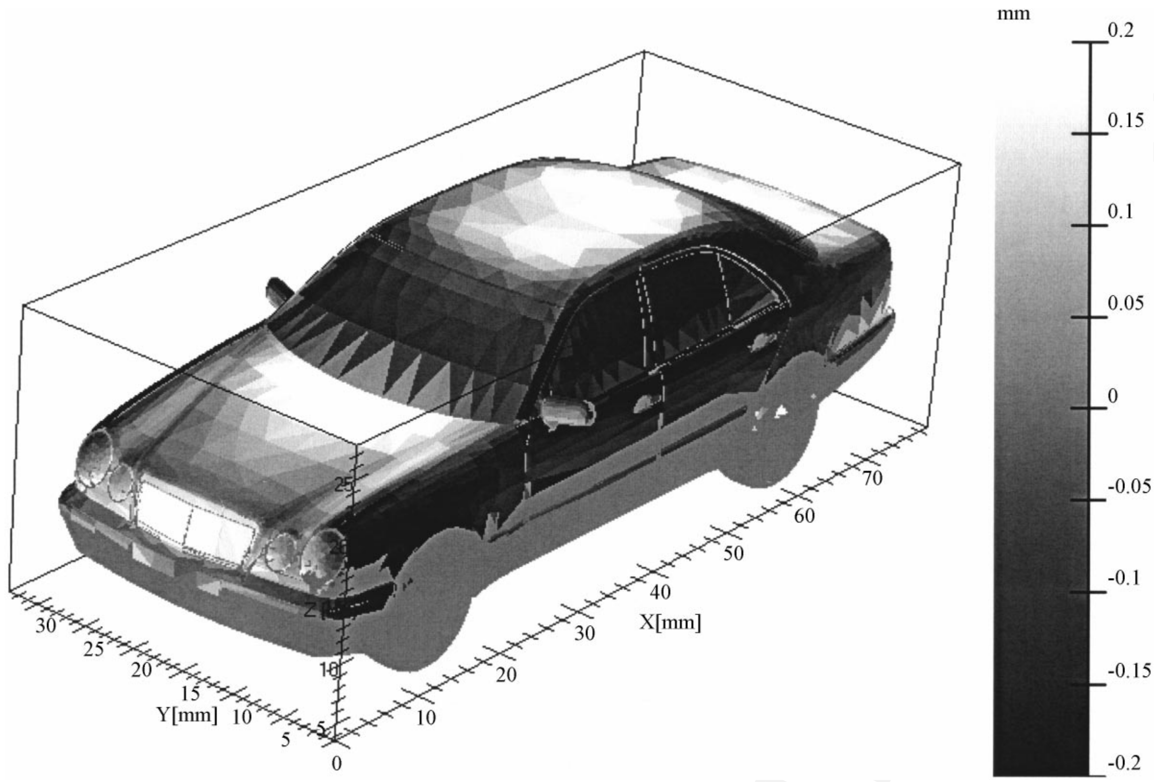

Fig. 18. Average difference of the CAD elements after registration.

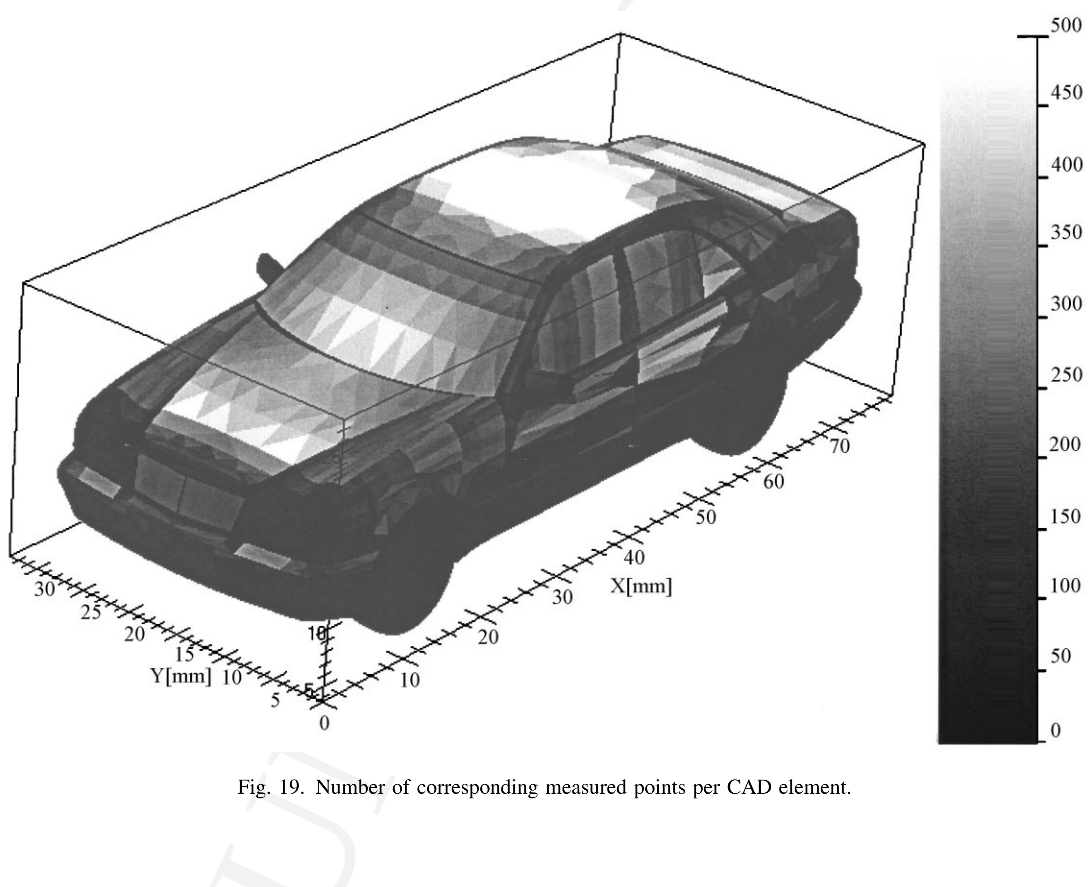

Fig. 19. Number of corresponding measured points per CAD element.

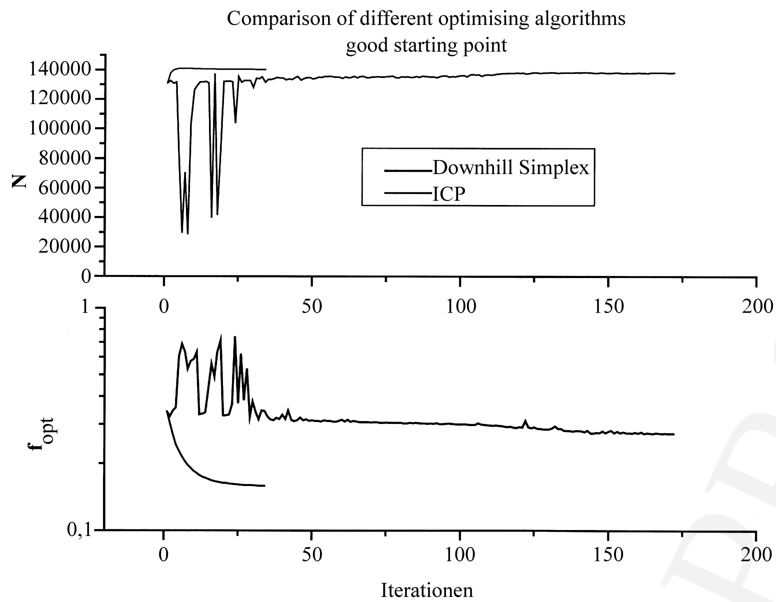

Fig. 20. Numerical optimization using the downhill simplex and the ICP algorithm with good starting values.

been moved, the sensor remains fixed). After the registration process is finished, the two data sets can simply be drawn into one image (cf. Fig. 24). Here, both images seem to fit quite seamless together which definitely indicates a good registration. With the ABW software package used for this project the registration process can be visualized online. That means, a graphic similar to Fig. 24 that shows current updates of the orientation can be seen while the registration process is running. This gives a good impression of the fitting strategy the different algorithms use.

If the relative orientations for all images that form a complete object have been defined pair-wise, the orientations for all images can be calculated within one coordinate system. Finally, an overall registration can be carried out to minimize the distances between all sub-images.

4. Application fields

The method presented in this paper can be used to support computer-aided quality control processes for all kinds of

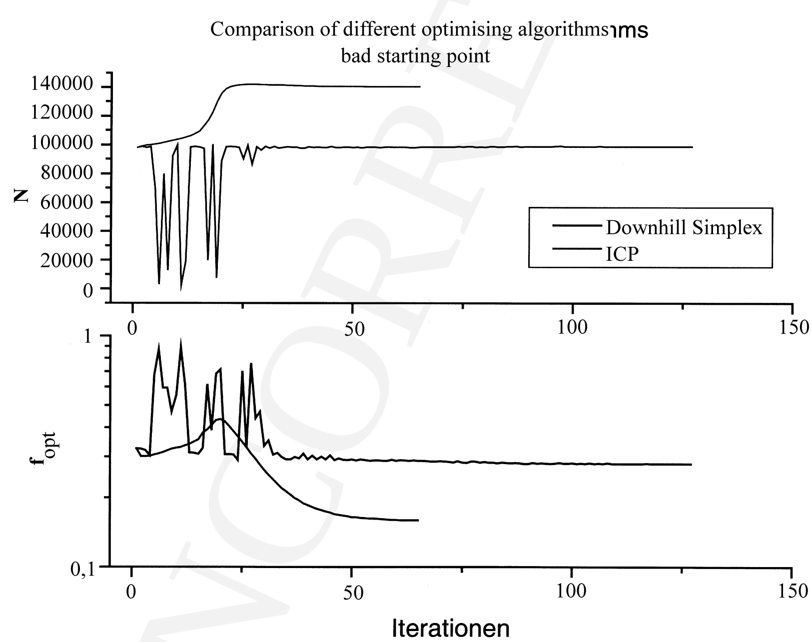

Fig. 21. Numerical optimization using the downhill simplex and the ICP algorithm with bad starting values.

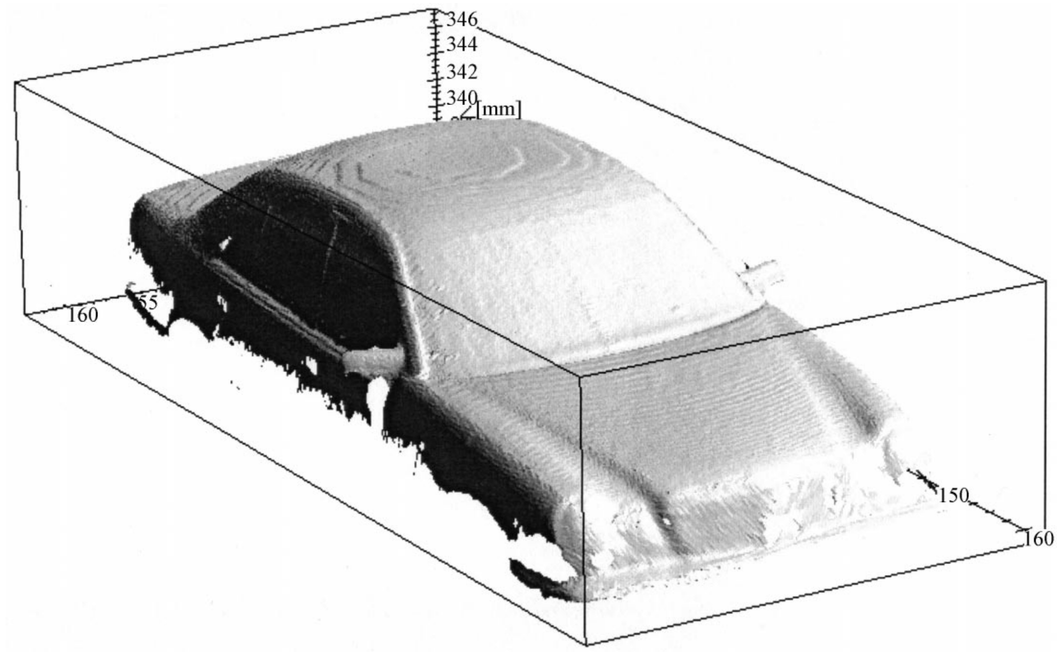

Fig. 22. First captured image of a car model (projection from top).

rapid prototyping or NC-manufactured objects. It is especially suitable for parts that contain free form surfaces. Today, CAQ and CAM are usually two independently performed processes within the CIM chain. However, the above-stated technique allows to integrate CAQ into CAM in order to make the overall product development process more efficient. The proposed approach can be used to monitor and control various tasks in line and mass production, e.g. tolerance analysis, exchange of worn out tools, etc. A description of such a metrology system used for rapid inspection of critical dimensions in high volume production can be found in [10]. Furthermore, for iterative processes (e.g. repair of damaged objects) a detailed measurement of the current object state can be obtained. Additionally, it is

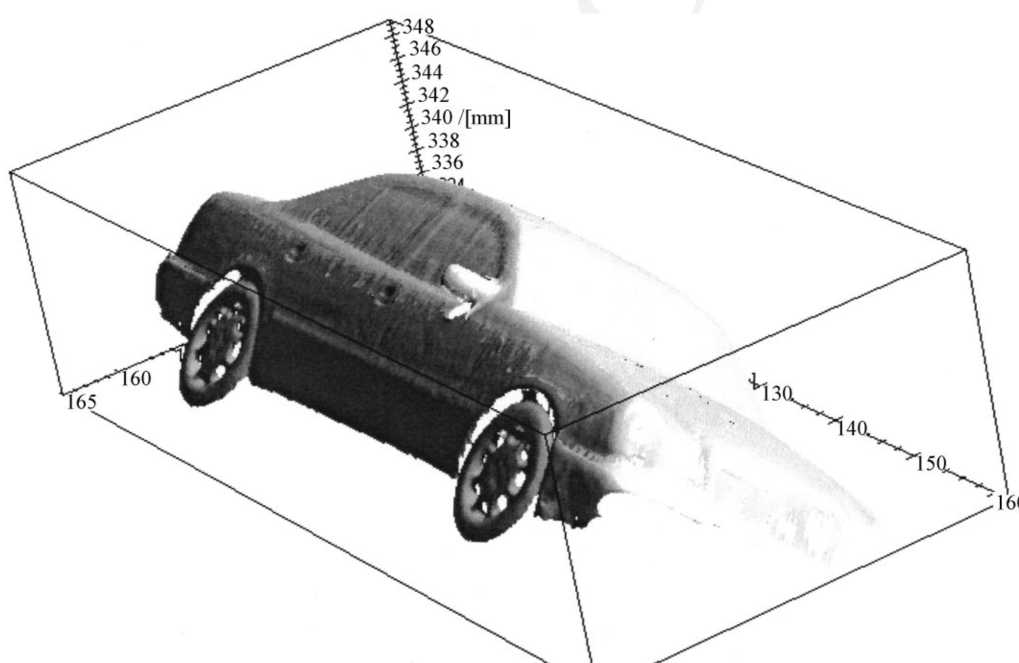

Fig. 23. Second captured image of a car model (projection from upper right-hand side).

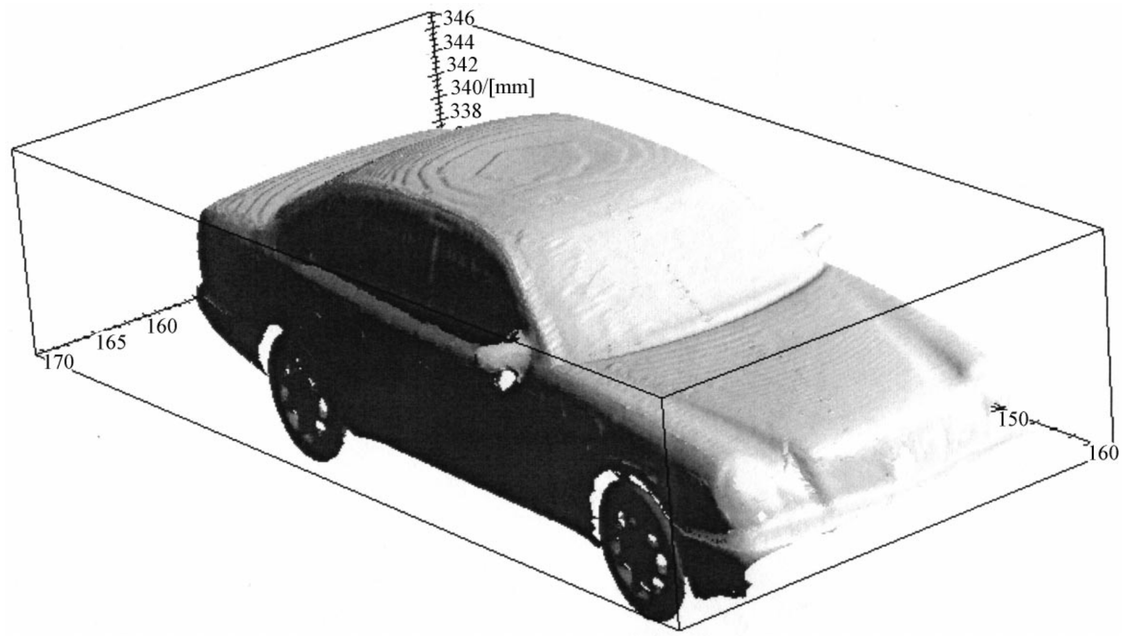

Fig. 24. Both measured data sets after registration drawn into one figure.

possible to verify the 3D sensor's accuracy by measuring known reference objects.

5. Conclusion

In this paper, an advanced CAQ approach for comparing manufactured objects with reference data from underlying CAD models has been presented. The related methods have been discussed, examples have been shown and application fields have been outlined. The suggested method has been implemented in a software prototype and the first test results are promising. Big effort has been made on the implementation of the visualization parts of these software tools. The 3D images shown in the examples above have all been rendered with OpenGL.

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